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# HUGH LE CAINE: PIONEER OF ELECTRONIC MUSIC IN CANADA

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Throughout history, technology and music have been closely related. Technological developments of many kinds have been used to improve musical instruments. Principles of mechanics and leverage were used in the 18th century to improve the harpsichord, for example, and resulted in the touch-sensitive keyboard of the pianoforte, a new instrument having a much greater possible range of dynamics.

The development of electronic technology in the 20th century was also adapted to the design of new musical instruments. Early mechanical devices such as Thaddeus Cahill's large synthesizer, the Dynamaphone, built in New York in 1906, were followed by electronic devices such as the Theremin and Ondes Martenot, keyboard instruments created in Europe in the 1920s.[1] In Canada, the pioneering work in this field is particularly associated with one person, Hugh Le Caine.

Le Caine was born in 1914 in Port Arthur (now Thunder Bay), Ontario. His father was an inventor and electrician who worked as an engineer at local grain elevators.[2] Young Hugh began to make his own experiments and inventions very early in life and developed an interest in building new musical instruments with the intention of obtaining 'beautiful sounds.' He built an electronic ukelele while studying at high school, where he studied music, playing the piano, organ and guitar, and sang in choirs. According to his recollections, Le Caine found out that he had perfect pitch one day when he became completely disoriented as he performed publicly on a piano tuned differently from the one at home. He reported that from then on he was used as a 'pitch pipe' by the choir conductor.

After high school, and a year of piano study in Toronto, he decided to enter the engineering-physics programme at Queen's University. It was there that he first learned how to describe the beautiful aspects of sounds in physical terms, through his studies of physics, acoustics and electronics. He remained active in music, particularly in organ playing, and made thorough studies of the attributes and shortcomings of the new electronic organs, such as the Hammond and the Robb Wave Organ. He built what he considered to be his first successful electronic instrument, an electrostatically-driven reed organ, at Queen's in 1937.[3]

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He was at this time working with J.A. Grey in the nuclear physics laboratory, and curiously, the device used for the organ was also applicable in the laboratory. From it Le Caine developed a device for making ionization measurements, the 'vibrating reed electrometer,' which later became a standard method of measuring ionization in physical laboratories all over the world.[4]

When Le Caine graduated from Queen's in 1939 with his MSc degree, there had been a job shortage due to the Depression and he felt he had been very lucky to obtain a post with the National Research Council (NRC) in Ottawa, where he worked on radar developments throughout the Second World War. During these years, all his activities in music came to a stop. The development of radar proceeded quickly, it was an exciting field and Le Caine gained early recognition for his participation in its development.

After the war he continued work at the NRC in microwave radio transmission and on the development of the microtron being built there. In his home studio he again began work on electronic musical instruments, first building a monophonic keyboard instrument. While it could only play one note at a time, it offered much greater control over the musical qualities of a tone than was available with existing instruments. Through its continuously variable wave-form control, the instrument produced a wide variety of timbres.[5]

Le Caine named his new instrument the electronic Sackbut, after a mediaeval wind instrument that was a precursor of the trombone. I believe this name was chosen at least partly because an important feature of the new instrument was its sliding pitch device, but in the footnote of an article about the instrument Le Caine said 'this choice of (the) name. . .of a thoroughly obsolete instrument. . .was thought to afford the designer a certain measure of immunity from criticism.'[6]

The first recording of the Sackbut was made in 1946, and by 1948 Le Caine had recorded a demonstration of the new instrument which shows it to have been a very impressive instrument, even by today's standards. There were recordings made that year of Le Caine and a few other physicists at NRC having 'jam sessions' in Hugh's home studio with the Sackbut, a piano and a clarinet, with multi-track recordings, reverberation and feedback. It is evident that they enjoyed themselves there. Incidentally, the use of multi-track recording, also heard on the Sackbut String Quartet example, was something of a technical breakthrough, and Le Caine built a special recording mechanism for that purpose.

Beginning in 1948, his work in electronic music went through another period of inactivity while he was studying on a NRC scholarship, earning his PhD in nuclear physics at Birmingham University in England. There, he found almost no interest in the new developments that were taking place in music, and he had stored all his own equipment in his parents' home in Port Arthur while he was away.

He began work in his home studio again as soon as he returned in 1952. He had given serious thought to the expressive qualities in music, and concluded that control over the dynamic shape of a note, its attack, decay and timbral qualities, forms a large part of the expressiveness of traditional monophonic instruments, like the violin, but was lacking on the more modern polyphonic instruments where several notes were played in unison. No continuous touch control had been successful for a polyphonic instrument. The possibility of having an inner part start soft and gradually become quite loud was an exciting one. Attack and decay might also be controlled by the performer.

Le Caine felt these problems could be resolved electronically, but he decided that any system of control had to meet the needs of a given performer and not the ideal an inventor might wish for. The force-sensitive keyboard was chosen as his solution, because it would beact to a performer's touch in much the same was as a piano action, the touch-sensitive keys controlling volume independently for each note. The instrument would also be able to play any combination of notes in unison as there would be a separate generator for each one.[7]

The prototype keyboard was a success, and in 1953 Le Caine decided that he wanted to devote himself full time to work on new electronic music instruments. He hoped he would be able to do this at the NRC and discussed the idea with E.W.R. Steacie, President of the NRC from 1952 to 1962. Steacie's attitude to scientific research has been described as 'of the old school.' He felt that the best way to achieve the highest standards in both pure and applied research was to hire the best scientists available and allow them to work in small groups on projects that interested them.

In the fall of 1953 Le Caine was asked to give a lecture to an audience of NRC staff, and demonstrate his new instruments. Then, in the spring of 1954 he gave his first public lecture at the NRC. He described his theories about 'expressive music,' addressing some of the common ground between science and music, two fields which had been at that time considered to be independent of one another. He discussed wave forms such as sine, triangle and square waves in musical terms. These waveforms were already familiar to radio engineers involved in circuit analysis and testing, but they were not considered at that time to have much musical potential. It must have been surprising for the scientists to hear Le Caine play convincing square wave melodies on the Sackbut. He also outlined the quantitative relations that make up musical sounds and their expressive characteristics. Since the normal playing of music was not usually thoughtof in physical or scientific terms, the musicians were probably as surprised as the scientists had been.

After the lecture Le Caine was asked by the audience members to imitate with the Sackbut such instruments as the piano, oboe and french horn. The success of the attempt depended upon how much he knew about the peculiarities of the instrument and the usual playing mannerisms. However, it was not his intention to imitate any instrument, exactly or otherwise, but to understand the mechanisms of expressive playing. He was more interested in what came to be called psychoacoustics, the study of the perception of sound. In anycase, the lecture was a success, and a few days later Steacie told Le Caine that he believed an electronic music project at NRC was a good idea.[8]

In the summer of 1954, Le Caine brought his Sackbut and his Touch Sensitive Organ (TSO) to the new location at the electrical engineering division, and immediately began work full time on improvements to the two instruments. Since both instruments had the potential to be manufactured and marketed by a Canadian company, Le Caine felt they were ideal projects for the NRC.

Le Caine habitually worked all night, arriving around 4.30 p.m. as the others were leaving for home. He was temperamentally suited to late night work. These working hours also ensured his privacy and prevented the sounds of his work from disturbing others. One result was that he became an enigma around the Council, and few of his associates knew him well or understood what he was working on, although they knew that his work was being recognized outside the Council.[9]

The instruments were taken on several lecture tours throughout Ontario and Quebec and they received good reponse from the press and from audiences.[10] The Sackbut stimulated particular interest. Dr John Pierce, who at that time edited the publication of the Institute of Radio Engineers, asked Le Caine to write a detailed article on his work, and when it was published in 1956, much more interest was generated.[11] Le Caine received several letters requesting information and prices from people interested in purchasing the Sackbut, but it was not possible to provide because no manufacturer had expressed interest in building it commercially. It seems there was little communication between Le Caine and Canadian industry, and apparently no attempt was made to stimulate it. We now recognize that the Sackbut was in fact the first 'synthesizer' and we know that when synthesizers became available in the late 1960s, twenty years after Le Caine built the Sackbut, there was indeed a market for them. However, its market potential was not evident at that time.

The TSO on the other hand, would have fitted into an already established market. Any one of the many manufacturers of electronic organs could have manufactured the TSO, and the interest would have been there since these companies were all trying to overcome what was a distinctly inferior sound compared to a pipe organ. The new TSO was intended to be similar to a pipe organ in every respect. It had a realistic organ sound, but it also provided the significant improvement of touch sensitive keys. Also of interest to the electronic organ companies was the natural sounding attack. All electronic organs at this time had an audible 'click' at the beginning of each note.

Le Caine's organ was ready to be presented at the 1955 Canadian Trade Fair were it was well received. In fact the Baldwin Organ Company bought a long term option on the patent, but they never used any of its timbral or touch sensitive features. After several years they brought out a click-less key design.[12] It is common for a company to buy out a patent simply in order to prevent a new innovation from being used by a competitor, and apparently this is what happened to the TSO with the Baldwin Company. A case can be made that the NRC should have sold the patent for a shorter period of time, to make it available to other manufacturers after a few years, but the NRC patent office was not experienced with such devices, and everyone concerned was probably pleased to sell the patent to Baldwin at the time. In defence of Baldwin, it should be noted that a new model of organ is very expensive to produce, requiring a large capital outlay which could be a loss if the instrument were a commercial failure. Yet if the instrument proved a success, the value of the stock in inventory would be reduced.

All work on the TSO was stopped, of course, when Baldwin bought the rights to it. But, at the same time, Le Caine's interests were shifting to the new forms of music that were being heard in Europe. Up to the mid-1950s he had used, in demonstrations of his instruments, only standard pieces or standard forms like the blues in order to show the recognizable musicality of the instruments. He extended the possibilities of expression within the existing repertoire by allowing more control to the performer as interpreter. However, there is no evidence that he used the Sackbut or the TSO to develop new ideas in composition, though the instruments, as we can see in retrospect, did offer many such possibilities.

At about that time Karlheinz Stockhausen completed his electronic studies at the Cologne electronic music studio, and Pierre Schaeffer and the *musique concrete* composers had several works broadcast after the 1948 'concert of noises' in Paris. Le Caine's first interest in composition was with the *musique concrete* technique. For this, recorded environmental sounds were used as the only musical material, altered by playback changes and some reverberation and then recombined into completed compositions. For these composers, pitch, harmony and rhythm in the commonly understood senses, had little relevance. A new sensibility, derived from the futurists of the early 20th century, was taking root. The technology of tape sound recording had greatly improved during the war, and in the late 1940s these tape recorders became available to composers. These were the technical sources of the new music which then began to blossom.[13]

An important change had occured in Le Caine's outlook as well. His primary interest was now in the new forms of music and thus in equipment to be used by composers of the new 'studio music' or 'tape pieces.' In 1955 Le Caine began work on a new instrument informally called the Multi-track. It was a development of his earlier multiple tape machine, and was concerned solely with the manipulation of sounds already recorded on tape. It was capable of playing ten stereo tapes stimultaneously, changing the playing speed and volume of each tape independently, and recombining the resultant sounds into a single stereo recording. It was in fact a 'multiple-tape' tape recorder, as opposed to a 'multiple-track' tape recorder and formally it was called the 'Special Purpose Tape Recorder.'[14]

Le Caine did not adhere to the distinction prevalent in Europe that natural sounds were for *musique concrete* while electronically-synthesized tones were for electronic music. He was prepared to use the multi-track tape recorder to process all sound recorded on tape, from whatever source. He was impressed by the results obtained by tape processing of natural sounds, but at the same time he realized that certain carefully controlled sounds could be obtained only by electronic means.

Late one night in December, 1955, Le Caine began work on his first composition. Using only the sound of the fall of a single drop of water as his raw material, he developed all the pitch, rhythmic and timbral material used in the composition with the new Multi-track. By 7.30 the next morning he had completed the new piece, *Dripsody*, and played it to his associates who arrived at work early that morning.

Following *Dripsody*, several more pieces were composed. *99 Generators* is noteworthy because it uses the TSO in the new music idiom, demonstrating sound resources outside the traditional musical repertoire that were available on the TSO without use of the Multi-track. Most of Le Caine's new pieces did use the Multi-track, however: *Invocation*, *Textures*, *The Burning Deck*, *A Noisome Pestilence*, *Study No. 1 for Player Piano and Tape*. The Multi-track could easily be adapted for use with many different styles of music. It was the most flexible tape recording mechanism ever built.

Both Le Caine's compositions and the Multi-track itself were given a great deal of attention in Canada and internationally. They were broadcast and played in concerts, and a description of the instrument was published in the *Journal of Music Theory*.[15] Other composers became interested in the NRC project; Istvan Anhalt, who now teaches at Queen's, was one of the first composers to work at the NRC facility. But the situation was not ideal, since the laboratory was not set up for the production of music; there was no provision for maintaining a studio with completed instruments in working condition. The laboratory also offered little privacy and there was always the possibility of disturbing other workers.[16]

In 1959, Dr Arnold Walter, director of the Music Department at the University of Toronto, met Le Caine and soon began to make arrangements to establish an electronic music studio at the university. He worked out an agreement with NRC whereby NRC and the university would share responsibility for the new studio.[17] The university provided the facilities and hired Myron Schaeffer to be the director of the studio. Le Caine's instruments were used and the NRC helped to maintain them and collaborated with composers there on the development of new instruments.

During in the 1950s some electronic compositions had been created at the Radio-Canada studios in Montreal and at the NRC laboratory in Ottawa, but the new studio at the University of Toronto was the first one in Canada to be devoted exclusively to the production of music. The studio greatly increased the availibility of Le Caine's instruments to composers and attracted many to work there. Later, the Folkways record company published an LP recording of works produced at the university.[18] This was one of the few electronic music studios in existence in 1959. There was one other studio in North America, the Columbia-Princeton Electronic Music Center in New York, and a few in Europe. At the University of Illinois some work on the computer generation of scores was being done, but in general electronic music studios were not common and by today's standards they possessed very little equipment: sound generators, microphones, tape recorders and some processing equipment. The Toronto studio was one of the best equpped and the Multi-track was the central focus of it.[19]

The Multi-track was in demand, and over the next few years several studios outside Canada, including Columbia-Princeton, wrote to Le Caine asking if they could make arrangements to buy one. The NRC was unable to manufacture instruments for sale as their mandate was to design new ones. The cost of the manufacture of each instrument would have been too high, and possible sales to studios to few to interest a commercial manufacturer. Eventually the NRC did build five Multi-tracks each with a slightly modified design and different custom-made parts. This took valuable time from the development of other instruments, but it was necessary to equip the university studios. In 1964 a studio was opened at McGill University, and a few years later a small one at Queen's was opened. Each studio had a Multi-track on semi-permanent loan from NRC.

Only one Multi-track was sent outside Canada. A new electronic music studio in Israel received it as a gift from the Canadian government to the State of Israel. It had been requested by composer Josef Tal who had worked with Le Caine in Ottawa.

Over the next ten years, twelve new instruments were designed for the university studios.[20] A significant aspect of the work on these new instruments, though not as visible as the instruments themselves, was the design of the component parts for use within the instruments.[21] Le Caine's designs are recognized for their accommodation to the needs of the human user rather than to the demands of the technology itself.

In 1967 Le Caine was asked to provide a participatory display of new electronic instruments for Expo 67 in Montreal, an exhibit which attracted much attention to his NRC work. He and his associates provided an interactive system with which the public could devise serial musical structures. All aspects of the music could be set in cyclic forms, with for example the rhythm and timbre varying as the melodic material was repeated.[22]

The last project that Le Caine worked on was a hybrid system, called the Paramus Music System, where the sound generators were controlled by computer input. This was another innovation that has become the standard method used by commercial synthesizers ten years later.

In the early 1970s the idea of manufacturing the Sackbut was revived. The Moog synthesizer and the Synthi AKS were now available, and in spite of the difficulties shared by all new instruments, they were selling well to university music studios and to composers and performers of popular and commercial music.

An attempt was made to interest a Canadian manufacturer in the Sackbut. The NRC patent office, which again, had had little experience with this type of product, awarded the contract to an inexperienced manufacturer with an agreement that Le Caine and his associates would assist the company in preparing to manufacture the instrument during an unspecified period of time. This turned out to be a heavy responsibility taking time away from the development of new instruments. After several years of meetings, adaptations in design and frustrating discussions of features to be added or removed, it was finally admitted that the instrument would never be manufactured. The failure of the Sackbut could be partially attributed to the long term of the patent agreement, and to the fact that the manufacturer was being subsidized to remain in the preparation stages but not to go ahead with production. A few other companies made enquiries about the Sackbut patents during this period, but since the patent had already been awarded, nothing could be done.

Because it was a large scientific organization, all negotiation for patents was done by the NRC's Canadian Patents Development Ltd. The arrangement freed the scientific staff from bureaucratic work, but it meant in this case that the design issues and manufacturing and marketing conditions applying to electronic music instruments were unfamiliar to the patent development office, accustomed to more recognizably scientific patents.

The failure of this attempt to manufacture the Sackbut was certainly a great disappointment to Le Caine. It must at times have seemed that his career in electronic instrument development had begun with one failure and ended with another one. Both the Sackbut and the TSO had failed to reach the commercial market although both of them were very high quality instruments, the first in their fields. Were Le Caine's achievements not evident to others? Perhaps his design work looked easy because of its apparent simplicity. There was nothing to compare his work with, and only experienced designers would realize how difficult it was to achieve simple effective solutions to complex problems of musical expression, performance technique and compositional practice

Instrument designers today, including Robert Moog, are still discussing the merits of touch sensitivity in keyboard instruments, and as yet no successful design has been manufactured.[23] It is worthy of note, however, that the interest in touch sensitivity and most other technological developments in music seems to be limited to composers writing original music. There may be a certain resistance to change on the part of musicians established in the standard repertoire and this reticence may have affected the commercial success of the Sackbut and the TSO because these instruments were to be directed toward that segment of the market. The instruments required practice and the development of some new techniques, but in general they were not difficult to play. They were certainly more accessible through traditional performance than the early synthesizers were.

At times Le Caine felt limited by the practicalities involved in the commercial manufacture of his instruments. A design had to be frozen at a particular stage in order to produce the first commercial model, but it was Le Caine's tendency to continually evolve an instrument and resist finalizing one particular design.[24] He could always see possibilities for improvement and was unwilling to accept the necessity to restrict the development of these possibilities. Perhaps his feeling that the instruments were imperfect prevented him from taking an active role in promotion of his work.

Although the manufacturing aspect of Le Caine's work was a failure, the other aspect, the design of new instruments for electronic music studios, was a success. The three Canadian studios trained a generation of composers in the use of new technology in music, and several of these have made their own contributions to the development of electronic music in the international community.[25] As a result, Canadians still maintain a high profile in electronic music.

Le Caine received international recognition for his work. He was awarded three honourary degrees at Canadian universities, and at Queen's University the new music building, Harrison-Le Caine Hall, was named in his honour. In 1974 he took an early retirement from NRC and for the next two years he pursued his interest in film but in 1976 was involved in a serious motocycle accident, and died as a result of it in the summer of 1977. His death was a considerable loss to music in Canada.

I would like to conclude with some speculations on the relation between innovation in science, technology and music as they relate to Le Caine's work. After the war, particularly in Canada, the public had a greatly increased respect for science, and government was willing to fund scientific work in universities and at the NRC. This public acceptance of scientific research combined with the insightful direction of Steacie, provided an ideal working environment of freedom and independence, and much was accomplished. It is clear that Le Caine could not have achieved what he did if he had not worked at the NRC. No private industry or university could have provided him with such freedom, not only to develop his ideas, but to work the hours he chose.

During the late 1960s and early 1970s, Le Caine's last years at the Council, policy changed somewhat. There was subsequently a greater interest in short-term results and in projects directly related to practical purposes with the expectation that the NRC could provide new manufacturing ideas to stimulate Canadian industry. During this period Le Caine composed few pieces. The majority of his compositions were done in the late 1950s. After the university studios opened it seems that he put himself and his NRC project at the service of composers who worked in the studios, designing equipment with which they could realize their ideas.[26] He was willing to leave composing to others, only writing music himself, he claimed, in order to gain an understanding of the processes involved. Although his main focus was the design of practical devices for composers and musicians, he was also interested in exploring the nature of sound and perception. I have been told that he lost interest in the Sackbut in the 1950s after he had learned from it what he wanted to learn about wave form and formant controls as they relate to music.[27] I believe this was his primary interest although he was very good at designing electronic circuits and other devices in every field he worked in, and was greatly respected for that ability.

Science in the twentieth century has been particularly reliant on technological innovation. Le Caine worked in nuclear physics in several locations during his career, and this field is extremely reliant on technological measuring devices of great accuracy. In traditional science, the hypotheses of the theorist are accepted only after they have been supported by the results of the experiment. The theoretical physicist is extremely reliant on technology, but the technologist is separated from the scientist in function. Le Caine complained while he was studying in England, that there were too many scientists, too few technicians, and that he found himself 'building filthy circuits,' just as he had done in Ottawa. His complaint implies that building, and I am sure, also designing circuits, was less important and less meaningful than the theoretical work. Derek DeSolla Price, in his spring 1983 lecture 'Sealing Wax and String,' pointed out that the role of scientific instruments and techniques has been seriously underestimated.[28] He suggested that scientific discoveries have not been basen on inductive and deductive reasoning, verified by experiment, nearly to the extent that they have been based on technological developments themselves, enabling new phenomena to be observed and then explained. In his view, the availability of innovative technology precedes new ideas, particularly in a field like nuclear physics that is so reliant on technology.

The distinction between scientistand technician breaks down in light of this hypothesis, and we can speculate that Le Caine had been straddling the distinction since his earliest years in science, even before he decided to combine the fields of music and science. If we extend Price's hypothesis to all innovation, including innovation in music, we can speculate on the relationship between Le Caine and the composers at the university music studios. At this time he had reduced his own activities as a composer and taken the role of providing technology to professional composers so that they could realize their ideas. It was assumed that the idea preceded the instrument.

In order for a composer to articulate an idea for a new electronic instrument that is innovative and at the same time realistic within the limits of the available technology, the composer would have to know a great deal about the technology itself and few of them do. Without this knowledge a composer will often confront an unfamiliar machine and gradually familiarize himself with its possibilities, eventually using some of them in compositions.

Through history, the successful new musical instruments have been those on which many compsers have been able to develop new musical possibilities. A successful instrument generally is one on which successful music is written, thus a successful instrument functions both as a result of the ideas of its designer and as a stimulus to the ideas of others. Le Caine's instruments enabled the composer to work with possibilities that did not exist previously, whether they presented new techniques or extended the range of pre-existent techniques.

In Le Caine's work, innovation in science, technology and music were closely interrelated. Throughout his career the development of innovative practical devices was closely linked with his interest in perception and expression in music. I have come to believe that his instruments were successful because they integrated these three areas of innovation.

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NOTES

1. Leon Dallin, *Techniques of Twentieth Century Composition* (Dubuque, 1974), 249-52.

2. Interview with Jeanne (Le Caine) Agnew, June 1983.

3. Hugh Le Caine, 'Recherches au temps perdu,' typescript autobiography (1964), 1-15. This MS, presently in the possession of Mrs Trudi Le Caine, is the source of much of the personal material in this paper.

4. Hugh Le Caine and J.H. Waghorne, 'The New Ionization Amplifier,' *Canadian Journal of Research* 19 (February 1941).

5. Le Caine, 'Recherches,' 27-43.

6. Hugh Le Caine, 'Electronic Music,' *Proceedings of the IRE* 46 (April 1956), 457.

7. Hugh Le Caine, 'The Touch Sensitive Keyboard for Organs,' *Canadian Journal of Music* (1959).

8. Interview with Trudi Le Caine, April 1981.

9. Interview with Horace Aubrey, October 1980.

10. National Research Council Archives, Le Caine Papers, Correspondence Files, 1954-55.

11. Cf. note 6.

12. Interview with Horace Aubrey.

13. Otto Luessing, 'Origins,' in J.H. Appleton and R.S.E. Perera, eds., *The Development and Practice of Electronic Music* (New York, 1975), 1-22.

14. Described by Le Caine in a conference paper entitled 'Tape Recorder for Use in Electronic Music Studios.' An abstract may be found in *Journal of the Acoustical Society of Ameri-*

*ca* (1959).

15. Hugh Le Caine, 'A Tape Recorder for Use in Electronic Music Studios and Related Equipment,' *Journal of Music Theory* 7:1 (1963).

16. Interview with Istvan Anhalt, October 1980; Interview with Horace Aubrey.

17. See correspondence of Le Caine and Walter in Le Caine Papers, Correspondence Files, 1958-60.

18. 'Electronic Music,' Folkways Records, FM 3436 (1967), contains a recording of *Dripsody*. *Mobile*, another composition, was recorded for the LP 'Carrefour,' of Radio-Canada International, No. 373 (now out of print).

19. Myron Schaeffer, 'The Electronic Music Studio of the University of Toronto,' *Journal of Music Theory* 7:1 (1963).

20. These instruments include: Sine Bank and Keyboard (ca. 1954-59); Spectrogram (ca 1958); Adjustable Filter (1962); Two Channel Alternator (1964); Ring Modulator (1964); Function Generator (ca 1964); Serial Sound Structure Generator (1965); Envelope Shaper (ca 1965); Tone Mixture Generator (ca 1967); Sonde (1968); Polyphone (1970); Paramus (1972-74).

21. Some important component parts include touch sensitive keys and keyboards, logarithmic resistor strips to control pitch and ensure accurate tuning, voltage controlled oscillators which hold a pitch without drifting, and pressure sensitive printed circuit keys operated by the conductivity of the finger of the performer.

22. Hugh Le Caine and G. Ciamaga, 'A Preliminary Report on the Serial Sound Structure Generator,' *Perspectives of New Music* 6:1 (1967); Le Caine, 'Apparatus for Generating Serial Sound Structures,' *Journal of the Audio Engineering Society* 17:3 (1969).

23. Interview with William Buxton, March 1983.

24. Interview with Trudi Le Caine, April 1981; Interview with David Rocheleau, March 1982.

25. The university studios were not devoted entirely to the production of music, their primary function being teaching. The heavy use by students limited the access of composers who worked independently. There is still no production studio for the use by graduates of the university studios.

26. Conversation with James Montgomery, April 1983.

27. Interview with Gordon Ellis, October 1980.

28. D.J. de Solla Price, 'Sealing Wax and String: A Philosophy of the Experimenter's Craft and its Role in the Genesis of High Technology,' AAAS Lecture (1983), Cassette No. 1983-3.